DOCUMENT RESUME

ED 444 837 SE 063 869

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TITLE Common Sense Clarified: Intuitive Knowledge and Its Role in Physics Expertise.
PUB DATE 1999-00-00
NOTE 16p.; Paper presented at the Annual Meeting of the National Association for Research in Science Teaching (Boston, MA, March 28-31, 1999).
AVAILABLE FROM For full text: http://www.narst.org/.
PUB TYPE Reports - Research (143) -- Speeches/Meeting Papers (150)
EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS Concept Formation; Higher Education; *Misconceptions; *Physics; *Problem Solving; Science Education

ABSTRACT

This paper introduces issues related to the role of intuitive knowledge in physics learning. Phenomenological primitives, which form the base level for intuitive explanations in the research, are discussed. Three primary questions are the focus of this paper: (1) What role, if any, does intuitive knowledge play in physics problem solving? (2) How does intuitive physics knowledge change in order to play that role, if at all? and (3) When and how do these changes typically occur? What are the crucial experiences that can lead to the "tuning up" of intuitive knowledge? In particular, can experiences with quantitative problem solving lead to changes in common sense physics knowledge? In the study, students were observed while solving a series of physics problems, and the sense of the mechanism site of their intuitive knowledge while problem solving was recorded. (Contains 12 references.) (YDS)

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ED 444 837

Common sense clarified:

Intuitive knowledge and its role in physics expertise

NARST Annual Meeting, 1999

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March, 1999

Introduction

"All truth, in the long run, is only common sense clarified." Thomas H. Huxley

Prior to any formal instruction, students have a great deal of experience that is relevant to the study of physics. They have interacted with the physical world, pushing and pulling, squeezing and pouring. They have talked about the physical world as part of everyday discourse. And they have acquired bits and pieces of more "formal" physics knowledge from the popular media as well as from earlier science instruction.

Research has documented that all of this experience leads to the development of a substantial body of knowledge concerning the physical world (e.g., Halloun & Hestenes, 1985; McCloskey, 1984; McDermott, 1984). Here, I will refer to this knowledge that is gained prior to formal instruction as "intuitive" or "commonsense" physics knowledge. Research on intuitive physics has been varied in the approaches that it adopts as well as in how intuitive knowledge is characterized. For example, some researchers have described intuitive knowledge in terms of a collection of preconceptions or misconceptions (e.g., Clement, 1984), while others have described studentsí prior knowledge as being a "naive theory" of the physical world (e.g., McCloskey, 1984). Nonetheless, a number of common themes and observations have emerged. For example, many of these researchers have noted the difficulties that students have with "passive" forces, as well as their tendency to presume, in various cases, that a force is required to sustain motion (McDermott, 1984). Furthermore, it has been widely contended that studentsí prior conceptions are robust and resistant to change during instruction (e.g., Smith, diSessa, and Roschelle, 1993).

While this work has been very revealing, it leaves open many important questions concerning the role of intuitive knowledge in physics learning and expertise. Research tells us that students have commonsense physics knowledge, and that this knowledge is often not greatly changed by instruction. But how much does this matter for the development of expertise? Is it possible that one can be a perfectly good physics expert while still having intuitive knowledge that conflicts with this expertise?

Of course, there are many reasons why this might not be the case. One worry is that, at the least, conflicting intuitive knowledge might "get in the way" of learning. In this view, intuitive knowledge must be addressed simply because it poses an obstacle to the acquiring of more expert knowledge. But, more dramatically, it is also possible that intuitive knowledge might

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play a crucial role in expert performance. In this alternative view, it is essential to address intuitive knowledge because this "improved" intuitive knowledge must ultimately form a component of expertise.

The purpose of this paper is to begin to address questions relating to these issues; I want to move beyond the study of the intuitive knowledge of novices to a focus on where and how intuitive knowledge gets built into expert physics understanding. Do experts continue to use their intuitive knowledge, in some manner, when they think deeply and carefully about physics? If so, how exactly does their intuitive knowledge differ from that of a novice?

I should emphasize that my goal is not to look at "informal" reasoning in experts, or even purely qualitative reasoning. Rather I want to study the very bastion of expertise: I want to begin to describe the role that intuitive knowledge plays in *quantitative* problem solving with equations, as students progress toward expertise. Three primary questions will be the focus of this paper:

1. What role, if any, does intuitive knowledge play in physics problem solving?
2. How does intuitive physics knowledge change in order to play that role, if at all?
3. When and how do these changes typically occur? What are the crucial experiences that can lead to the "tuning up" of intuitive knowledge? In particular, can experiences with quantitative problem solving lead to changes in commonsense physics knowledge?

To anticipate what follows, I will primarily answer my three questions in the affirmative. I will argue that intuitive physics knowledge plays a variety of roles in expert problem solving; in fact, I will maintain that it can even drive work with equations in a fairly direct manner. Furthermore, I will try to show that intuitive knowledge needs to change in order to function as a component of expertise. However, I will argue that there are important limits on how much it is really necessary for intuitive knowledge to be made "correct:" it must only be adapted so as to support and complement work with equations.

It is worth taking a moment here to emphasize the nature of what I will be maintaining: I will be arguing that intuitive physics knowledge ñ knowledge gained, in part, from our everyday experience pushing and pulling things in the physical world ñ plays a role in what we might have thought was the purely formal process of physics problem solving.

In part, the significance of this work comes from bridging two varieties of research. In looking at the role that intuitive knowledge plays in problem solving, I am spanning earlier research on physics problem solving (e.g., Chi, Feltovich, & Glaser, 1981; Larkin, 1983) and research on intuitive physics knowledge. To a large extent, these bodies of research have remained separate, with a few notable exceptions. One of these exceptions is the work of Clement (1994), who has attempted to demonstrate the importance of a variety of intuitive knowledge in expert reasoning, including what he calls "imagistic simulations." However, Clement does not undertake to describe how intuitive knowledge must *evolve* for its role in expertise.

Outline of this paper

In the remainder of this paper, I will set out to answer the three questions stated in this introduction. I will begin with some theoretical preliminaries. In order to initiate this endeavor, I need to adopt a viewpoint on the nature of intuitive physics knowledge. For the purposes of this work, I will adopt a framework that was proposed by Andrea diSessa (diSessa, 1993). That framework is described in detail in the next section.

diSessaís framework describes the intuitive knowledge of physics-naive subjects, and is based on observations of novices. Following my introduction to diSessaís framework, I will look at the intuitive knowledge of more expert subjects in the context of problem solving. To make my points, I will present a few extended episodes from the work of specific subjects. In the first of these episodes, intuitive knowledge will be seen to play a somewhat ancillary role. In subsequent examples, we will see intuitive knowledge playing a more direct and intertwined role in the problem solving process.

Finally, in the last major section of this paper, I will argue that a new type of knowledge needs to develop in order to mediate the role that intuitive knowledge plays in expert problem solving.

Theoretical Background

In setting out to answer the above three questions, I will adopt a particular viewpoint. First, following Smith, diSessa, and Roschelle (1993) I will adopt a complex systems view on the nature of knowledge. In *Misconceptions reconceived* , these authors present an argument for "an analytical shift from single units of knowledge to systems of knowledge with numerous elements and complex substructure that may gradually change, in bits and pieces and in different ways." In this view, intuitive physics knowledge is a complex system consisting of many elements. Some of these elements will be appropriate elements of expertise, and some will not. Furthermore, the entire intuitive knowledge system will require changes in order to form a component of expert physics knowledge, which is itself a complex system.

I adopt this perspective, because I believe it is necessary in order to see the potentially productive role of intuitive physics knowledge. If we were to presume, instead, that intuitive knowledge consisted of a small number of structures with very wide applicability (either a "theory" or a small set of beliefs), then it would be difficult to see how intuitive knowledge could play any productive role. Since these beliefs are strictly incorrect, they would need to be cast out in favor of more appropriate beliefs. On the other hand, if we presume that intuitive knowledge is a complex system consisting of many elements, then it is possible

that some of the elements may have a productive role, even though others will need to be eliminated or modified.

One effect of adopting this viewpoint is that it tends to erode any strong divide between "novice" and "expert." In this view, learning physics does not involve the casting out of novice knowledge in favor of an expert body of knowledge that is of an entirely different sort. Instead, the image is one of gradual evolution of a complex system, with the end result being an expert body of knowledge that bears many deep similarities to the knowledge of novices.

For the purpose of this paper, I will not be able to consider all aspects of intuitive physics knowledge or all viewpoints on the nature of intuitive knowledge. There are too many viewpoints in the research literature to consider them all here, and the breadth of our everyday knowledge about the physical world is potentially vast. For that reason, I will narrow my focus to a portion of intuitive physics for which diSessa (1993) has given a complex systems account.

In his *Toward an epistemology of physics* , diSessa focuses his attention on a subset of intuitive physics knowledge that he calls the "sense-of-mechanism." The sense-of-mechanism is a part of our intuitive physics knowledgeóthe knowledge that we gain through our day-to-day experiences in the physical world. One function of this knowledge is to contribute to our ability to interact in the physical world; it plays a role in the pushing, pulling, throwing, and pouring that we do in order to live in the world. But the sense-of-mechanism also has some functions that apply more obviously and directly to physics learning: It allows us to judge the plausibility of possible physical events, make predictions, and it plays a crucial role in our construction of explanations of physical events.

The sense-of-mechanism consists of knowledge elements that diSessa calls "phenomenological primitives" or just "p-prims" for short. They are called "primitives" because elements of the sense-of-mechanism form the base level of our intuitive explanations of physical phenomena. As an example, diSessa asks us to think about what happens when a hand is placed over the nozzle of a vacuum cleaner. When this is done, the pitch of the vacuum cleaner increases. According to diSessa, the way people explain this phenomena is they say that, because your hand is getting in the way of its work, the vacuum cleaner has to start working much harder. The point is that this explanation relies on a certain primitive notion: Things have to work harder in the presence of increased resistance if they want to produce the same result.

diSessaís program involves the identification of these primitive pieces of knowledge ñ the p-prims. In the case of the vacuum cleaner example, the typical explanation boils down to an appeal to what diSessa calls *Ohmís p-prim* as the basis for the explanation. In *Ohmís p-prim* , the situation is schematized as having an agent that works against some resistance to produce a result. The idea is that *Ohmís p-prim* provides the primitive basis for this typical explanation; the explanation goes precisely this deep and no deeper.

The "phenomenological" part of "p-prim" also merits some comment. P-prims are described as phenomenological because they develop out of our experience in the physical world. We have many experiences in the physical world, pushing and lifting objects, and p-prims are abstractions of this experience. Furthermore, once they are developed, we come to see p-prims in the world. In sum, p-prims are basic schematizations of the physical world that we learn to see through repeated experience in the world.

Force and Agency	**Constraint Phenomena**
ohmís p-prim	*blocking*
spontaneous resistance	*supporting*
force as mover	*guiding*
dying away	
Balance and Equilibrium	
dynamic balance	
abstract balance	

Figure 1 . A sampling of p-prims.

The variety of p-prims

In order to give a feel for the variety and scope of phenomena covered by the sense-of-mechanism, I want to discuss a selection of p-prims (refer to Figure 1). I begin with some p-prims from what diSessa calls the "Force and Agency" Cluster. *Ohmís p-prim* is an example of a p-prim in this cluster. Recall that in *Ohmís p-prim* a situation is schematized as involving some agent that works against a resistance to produce a result. A related p-prim in this cluster is *spontaneous resistance* . The

resistance in *spontaneous resistance* is different than that in *Ohmís p-prim* because it is intrinsic to the object of some imposed effort. For example, the difficulty that we have in pushing a fairly heavy object can be attributed to *spontaneous resistance*. Compare this to the resistance that is imposed by a hand in the vacuum cleaner situation.

I want to mention two other p-prims in the Force and Agency cluster. The first, *force as mover*, has clear relevance to physics learning. In *force as mover*, a push given to some object is seen as causing a movement of the object in the same direction as the push. In some circumstances, the predictions made by *force as mover* agree with Newtonian physics, but, in other circumstances, *force as mover* contradicts the predictions of Newtonian physics. According to Newtonís laws, an object only moves in the direction of an applied force if the object is initially at rest, or if the push happens to be in the direction that the object is already moving. Otherwise, the applied force will deflect the object.

The final p-prim I want to mention in the Force and Agency Cluster is *dying away*. Like *force as mover*, this p-prim is associated with the drawing of non-Newtonian conclusions about the world. The idea behind *dying away* is that all motion must, in due time, die away to nothing. In contrast Newtonís laws predict that, in the absence of any applied forces, objects in motion continue to move indefinitely.

A second cluster of p-prims pertains to constraint phenomena. These p-prims explain phenomena by appeal to the constraints imposed by the geometric arrangement of physical objects. For example, if a rolling ball runs into a wall, the ball stops. We might explain this by saying that the wall blocked the ballís motion, or the wall simply "got in the way." This is an application of the *blocking* p-prim. Compare this explanation with one that states that the ball stopped because the wall applied a force to it.

Another p-prim in this cluster, *supporting*, is a special case of *blocking* in which the motion opposed, or the motion that would have happened, is due to gravity. Why doesnít a book placed on a table fall? Because the table *supports* it.

The last p-prim from this cluster that I will mention is *guiding*. As an example, imagine a metal ball rolling in a groove made in a wood surface. It is not surprising to us that the ball follows the path of the groove. Note, again, that we explain this without appeal to forces; the groove simply guides the ball because of its geometric nature.

Finally, I want to mention two p-prims from the "Balancing and Equilibrium" cluster. The first of these p-prims is *dynamic balance*. A situation involving two equal and opposite forces would likely be explained by appeal to this p-prim. diSessa contrasts this p-prim with a second that he calls *abstract balance*. In *abstract balance*, the balancing of the quantities involved is required either by the definition of these quantities (as in one kilogram is 1000 grams), or because of universal principles (such as the conservation of energy). As diSessa says: "abstractly balancing things should or must balance; dynamic balancing is balancing by accident or conspiracy."

A mechanism for p-prim activation

The above discussion is designed only to provide a feel for the scope of the sense-of-mechanism. diSessaís list is somewhat longer and he suggests where many p-prims exist beyond those that he names. My listing of p-prims will end here, however, and I will instead move on to another piece of diSessaís account of the sense of mechanism. To this point, I have not said very much about the mechanism that determines which p-prims get used at which time. So far, the only mechanism that we have is "recognition," p-prims are just "seen" in circumstances.

But diSessa extends his account beyond the simple statement that p-prims are recognized. The key question is when and how a p-prim is "cued to an active state." diSessa argues that the activation of a p-prim depends on other aspects of the current "mental context," which includes what we perceive in the world, what other p-prims are active, and any additional active knowledge, including "conscious ideas." Furthermore, diSessa defines two terms that are designed to provide characterizations of how likely a given p-prim is to be activated. The first of these terms, "cuing priority," describes the likelihood that a given p-prim will be activated given some perceived configuration of objects and events in the world. The second term concerning p-prim activation that diSessa defines is "reliability priority." Reliability priority provides a measure of how likely a p-prim is to stay activated once it is activated. The point is that, once a p-prim is activated, this activation contributes to a subsequent chain of mental events that may or may not involve the p-prim continuing to be activated. Taken together, cuing priority and reliability priority constitute what diSessa calls "structured priorities."

Although diSessa talks in the language of structured priorities throughout most of *Toward an epistemology of physics*, he also provides a model of the sense-of-mechanism as a connectionist network. P-prims are nodes in the network and there are weighted connections between these nodes. Given this model, cuing and reliability priority can be reduced to behavior of the network due to the values of these various weightings. Thus, in principle, we could discard the language of structured priorities in favor of descriptions given solely in terms of this connectionist network. diSessa argues, however, that is worth retaining "cuing priority" and "reliability priority" as technical terms because these terms provide qualitative characterizations of the connectionist network that are more easily put in correspondence with human behavior. For example, given the activation of a high *reliability* p-prim, a person is more likely to stick to their characterization of a situation in terms of this p-prim, and to assert a high level of confidence for this characterization.

Speculations concerning the development of the sense-of-mechanism

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The preceding sections summarize the basic account of the sense-of-mechanism given in diSessa (1993), which is based on diSessaís observations of physics-naive subjects. The above account stops short of describing what happens to the sense-of-mechanism during the learning of formal physics, and diSessa lacks any direct observations of expertise on which to base any conclusions. However, with this detailed account in hand, we can begin to speculate as to what might happen to the sense-of-mechanism; at the least, we can lay out the *a priori* possibilities for change. In fact, diSessa does engage in just such speculations. In this section, I briefly summarize diSessaís speculations concerning how the sense-of-mechanism may develop during the learning of physics, and I add some of my own speculations. Then, in the remainder of this paper, I look for evidence of these changes by examining the behavior of more expert subjects.

1) *Weightings change and the sense-of-mechanism is restructured.* One type of development that might occur is changes in the weights in the connectionist network, which can alternatively be thought of as changes in the priorities of individual elements. So, p-prims that werenít used very often, might come to be used more often, and some p-prims might have their priorities decreased so that they are used less, or not at all. This might happen through incremental adjustments to the weighting values that occur during repeated experiences in physics instruction.

Although the changes that occur during individual learning experiences may be small, diSessa believes that these incremental adjustments ultimately lead to a change in the overall character of the p-prim system. Before any physics instruction the sense-of-mechanism is relatively flat, it has only very local organization with individual p-prims having connections to only a few others. Certainly some p-prims have higher priorities than others do, but there are no central p-prims with extremely high priority.

With the development of expertise, this situation may very well change. diSessa hypothesizes that the priority of some elements is greatly increased and the priority of others greatly decreased. The result is a system with central, high priority elements. Thus, there is a change in the character of the sense-of-mechanism; it undergoes a transition from having little structure to having more overall organization.

2) *New p-prims develop.* As students learn to attend to different pieces of the world and their experience, new elements may be added to the sense-of-mechanism.

3) *P-prims take on new functions.* The new activities associated with classroom physics and the new types of knowledge that are acquired provide opportunities for p-prims to perform new functions. For example, p-prims may come to serve as "heuristic cues" for more formal knowledge; when a p-prim is cued it can lead more or less directly to the invocation of some formal knowledge or procedure. In addition, p-prims may play a role in "knowing a physical law." For example, we may in part understand Newtonís second law and $F=ma$ through *spontaneous resistance*, the tendency of objects to continue moving in the direction that they are already moving.

This type of change is very important for the story that I am developing in this paper. In succeeding sections, I will attempt to show that, because they take on new functions, p-prims can play a role in physics problem solving. In fact, beyond serving as heuristic cues to formal knowledge as diSessa speculates, I will attempt to show that p-prims can drive problem solving in a fairly direct manner.

The idea is that all of these changes will be directed toward producing a physical intuition that is refined and somewhat adapted for use in expert physics. diSessa also provides a wealth of details concerning the specific refinements that he expects to occur, of which I will only mention a few. Some parts of the sense-of-mechanism can have little use in expert physics and thus should be substantially suppressed. For example, in expert physics, constraint phenomena are no longer explained by a simple appeal to the geometry of objects. Instead, these phenomena must be explained in terms of forces applied by obstructing objects. Thus, the priority of p-prims, such as *blocking*, that were previously associated with constraint phenomena should be greatly decreased, and the cuing priorities of p-prims in the Force and Agency Cluster should be increased for these circumstances.

The changes associated with constraint phenomena are typical of a more widespread trend predicted by diSessa. He conjectures that, in general, the role of agency will be greatly expanded in the sense-of-mechanism. As students learn to see more and more circumstances in terms of forces, the range of application and priority of p-prims in the Force and Agency Cluster will be increased.

Data corpus and analysis

In the above section, I described diSessaís model of the sense-of-mechanism, which is based on observations of physics-naive subjects, as well as his speculations concerning how the sense-of-mechanism must develop with expertise. Now I begin my empirical investigation of the role of p-prims in expertise, and especially in problem solving. As stated in the introduction, I want to see what roles intuitive knowledge plays in expertise, how it changes to play that role, and what experiences can lead to those changes.

The work reported on here is part of a larger project directed at studying the meaningful use of equations in physics (Sherin, 1996). That project was based around a data corpus involving observations of moderately advanced (third semester) university

physics students. The work of five pairs of students was videotaped. Each of these pairs was observed as they worked, while standing at a whiteboard, to solve a series of physics problem. On the average, the pairs required approximately 5 1/2 hours each to complete the problems (spread over a number of session), thus resulting in a total of 27 hours of videotape. The videotapes were transcribed for analysis.

The problems given to the subject were, for the most part, relatively typical textbook physics problems, though a few more unusual tasks were also included. A subset of these tasks, consisting of the seven problems listed in Table 1, were selected for more focused analysis. In the following sections of this paper, examples are selected from student work on these tasks.

1. Shoved Block	A person gives a block a shove so that it slides across a table and then comes to rest. Talk about the forces and whatís happening. How does the situation differ if the block is heavier? (Assume that the heavier block starts with the same initial speed.)
2. Vertical Pitch	(a) Suppose a pitcher throws a baseball straight up at 100 mph. Ignoring air resistance, how high does it go? (b) How long does it take to reach that height?
3. Air Resistance	For this problem, imagine that two objects are dropped from a great height. These two objects are identical in size and shape, but one object has twice the mass of the other object. Because of air resistance, both objects eventually reach terminal velocity. (a) Compare the terminal velocities of the two objects. Are their terminal velocities the same? Is the terminal velocity of one object twice as large as the terminal velocity of the other? (Hint: Keep in mind that a steel ball falls morè quickly than an identically shaped paper ball in the presence of air resistance.)
	(b) Suppose that there was a wind blowing straight up when the objects were dropped, how would your answer differ? What if the wind was blowing straight down?
4. Mass on a Spring	A mass hangs from a spring attached to the ceiling. How does the equilibrium position of the mass depend upon the spring constant, k, and the mass, m?
5. Stranded Skater	Peggy Fleming (a one-time famous figure skater) is stuck on a patch of frictionless ice. Cleverly, she takes off one of her ice skates and throws it as hard as she can. (a) Roughly, how far does she travel? (b) Roughly, how fast does she travel?
6. Buoyant Cube	An ice cube, with edges of length L, is placed in a large container of water. How far below the surface does the cube sink? (ρice = .92 g/cm3; ρwater = 1 g/cm3)
7. Running in the Rain	Suppose that you need to cross the street during a steady downpour and you donít have an umbrella. Is it better to walk or run across the street? Make a simple computation, assuming that youíre shaped like a tall rectangular crate. Also, you can assume that the rain is falling straight down. Would it affect your result if the rain was falling at an angle?

Table 1 . Tasks selected for the focus analysis.

It is important for me to comment on why I chose to look at third semester physics students rather than true experts, such as professors or advanced graduate students. In short, this choice arises from the fact that my intention is to get a handle on a broad process of change; I want to understand how intuitive knowledge develops during physics learning. An optimal approach would have been a longitudinal study or, at the least, an approach that involved looking at subjects at a variety of stages. But, since this was not logistically possible, I chose to focus on subjects at an "in between" level of expertise, with the hope that I would be able to observe some of the behaviors that are characteristic of expertise, while also having the opportunity to observe ongoing processes of learning.

In this paper, I will not report systematically on the full analysis of the data corpus. The new work reported on in this paper is based on detailed microgenetic analyses of selected episodes from the corpus, rather than corpus-spanning or comparative analyses. In this detailed analysis of episodes, my purpose is to track, in detail, the role of p-prims in problem solving, and look for evidence of change during individual episodes. For a more complete and systematic analysis of the corpus refer to Sherin (1996).

P-prims and problem solving: A first example

I am now ready to present my first example in which we will look for intuitive knowledge ñ p-prims, in particular ñ in the

context of quantitative problem solving. In this first example, we will see that the sense-of-mechanism is active, though in a somewhat ancillary role. Ultimately, will want to see that intuitive knowledge can be intertwined in the details of problem solving, and can play an absolutely essential role. Nonetheless, this is a useful example to begin with because the role of intuitive knowledge is very clear.

In addition to noticing that p-prims are active during problem solving, I will make some more speculative observations. First, I will comment on how the intuitive knowledge of these moderately advanced subjects appears to be different from that of truly naive subjects. Even more speculatively, I will comment on how the intuitive knowledge of these subjects might be changed by the very experience under consideration in this episode.

In the episode under consideration here, a pair of students, Alan and Bob, were working on the Shoved Block problem (refer to Table 1). In this problem, two blocks, a heavier one and a lighter one, are given a shove and then they slide across a table, eventually coming to rest (see Figure 2). Furthermore, the blocks are shoved in such a way that they start off with the same initial speed. The question to consider is: Which block travels farther?

In response to this question, the subjects in the study stated two intuitions. One of these intuitions was that the heavier block should travel a shorter distance since it experiences a greater frictional force. The second intuition was that the heavier block should travel a greater distance since heavier things are "harder to stop." In actuality, in a perfect Newtonian world, it turns out that these "effects" precisely cancel, and the two blocks travel the same distance.

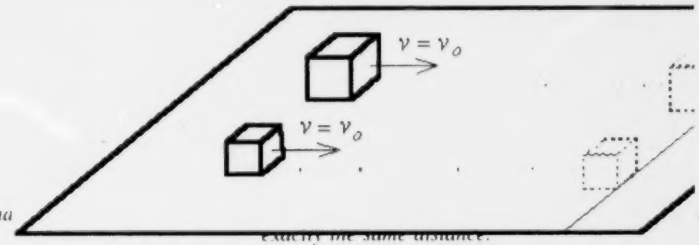

Figure 2 . A heavier and a lighter block are given the same initial speed, they travel exactly the same distance.

In their work on this problem, Alan and Bob began by clearly stating these two competing intuitions. (Refer to Appendix A for a key to codes used in the transcripts.)

> *Alan* And then if the block was heavier, it'd just mean that our friction was greater, and it would slow down quicker.
>
> ---
>
> *Alan* That seems kind of- Something seems strange about that because if you had like a block coming at you, a big heavy block, and a small lighter block. Two different instances. And you have this big heavier block coming toward you and you want it to slow down, it certainly takes much more force for you to slow down the bigger heavier block than the - the lighter one.
>
> *Bob* Oh wait, that's true!
>
> *Alan* Because, even though they're both working on the same frictional surfaces, just logically I know the big heavier block takes-, I mean football is all about that, that's why you have these big three hundred pound players.

Having stated these conflicting intuitions, Alan and Bob were faced with the task of determining which of these intuitions is correct. To do this, Bob began by first writing only the equation $F=ma$. He drew an arrow upward under the F and the M, and used the equation to consider what would happen if each of these parameters increased.

$$F = ma$$
$$\uparrow \quad \uparrow$$

> *Bob* I mean, F is obviously going up as you get um - The frictional force is going up as you get heavier, and the mass is going up. So, I mean it depends if.

This first attempt at using an equation to resolve the conflict was inconclusive. If the force increases, this suggests that the acceleration should increase, but the increasing mass suggests the reverse. Because this first attempt failed, Alan and Bob went on to produce a more complete solution to this problem. As shown in Figure 3, they began by writing an expression for the force of friction, F_f, then they substituted this expression into $F=ma$. Canceling the mass in the equation obtained produced an expression for the acceleration of the block: $a=g\mu$. *(Here, "μ" is a constant parameter known as the "coefficient of friction.")* It is important to notice that this expression does not depend on the mass of the block, which suggests that the motions of the heavier and lighter blocks are completely the same.

$$F_f = m g \mu$$
$$m g \mu = m a$$
$$a = g \mu$$
$$F_f = m a$$
$$\uparrow \quad \uparrow$$

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Figure 3 . $F_f = m g \mu$ *A Block problem.* $m g \mu = m a$

Alan and Bob were themselves aware of this im $F = m a$

Bob *So, I mean the masses drop out.*

Alan Right, so, actually, they should both take the same.=

Bob =Wait a minute. Oh, they both take the same! [Surprised tone]

O

Bob So, no matter what the mass is, you're gonna get the same, the same acceleration.

So, in this little episode, Alan and Bob have resolved this conflict between two intuitions in a way that is a little surprising to them. It turns out that neither intuition is exactly right, both blocks travel exactly the same distance.

While this completes most of what I want to relate concerning Alan and Bobís work on this task, I want to also talk about this episode in terms of p-prims. The first intuition ñ that the heavier block slows down faster ñ can be considered to be a somewhat refined application of *force as mover* ; the presence of the frictional force causes the block to slow down. The second intuition involves the *spontaneous resistance* p-prim; the block has an intrinsic resistance to changing its speed by slowing down. In addition, both intuitions probably involve the activation of *Ohmís p-prim* since there is an effort working against a resistance to produce a result. But this last p-prim is applied somewhat differently in each instance. In the case of the first intuition, the change in intrinsic resistance is not a salient aspect of the difference between the heavy block and light block situations. Only the change in force is noticed, not the change in resistance.

Next, I will discuss this episode from the point of view of the three questions raised in the introduction:

1. **What role, if any, does intuitive knowledge play in physics problem solving?**

   We have seen that intuitive knowledge was active during Alan and Bobís work on the Shoved Block problem. The students could have begun by just immediately writing equations but, instead, they initially stated their intuitions concerning the outcome. It is possible that this situation is slightly unusual since the question was stated in qualitative terms. However, Alan and Bob did not behave as if their performance was particularly anomalous and this behavior was certainly not much of a stretch for them.

   Nonetheless, it must be admitted that intuitive knowledge did not play a very central role in the aspects of the problem solution that involved equations. It does seem that they could just as easily have solved this problem without the stating of intuitions at the beginning. However, this does not mean that the role of intuitive knowledge was completely unimportant. In this case, it provided a motivation for the work and a context for interpretation. Notice that it was in terms of the competing intuitions that Alan and Bob understood the outcome of their problem solution.

2. **How does intuitive physics knowledge change in order to play that role, if at all?**

Given this episode, it is possible to make some comments concerning how the sense-of-mechanism changes for expertise. Notice that although I described Alan and Bobís initial comments as "intuitive," these comments are indicative of a somewhat refined intuition. First, we should realize that a complete novice might explain this motion by an appeal to entirely different p-prims such as *dying away*. If we apply *dying away* to explain the shoved block then we state that the motion dies away simply because that is what motions do. In contrast, Alan and Bob are capable of attributing the slowing down of the block to a particular agent, a force applied by the table. This suggests significant progress in the direction of expertise; it is a move toward an emphasis on agency, as predicted by diSessa.

Second, Alan and Bob applied the p-prims that they did use in a somewhat refined manner. The use of *force as mover* to account for *changes in speed* rather than as an explanation for *motion in some direction* constitutes a refined use of this p-prim. Similarly, they applied spontaneous resistance to describe an objectís intrinsic resistance to changes in speed. Again, this suggests progress in the direction of expertise.

I also want to draw out one very general moral concerning how intuitive knowledge must change for expertise. Although this episode suggests that Alan and Bobís intuitive knowledge is more developed than that of a complete novice, it is likely that their intuition is still not up to the level of expertise. (In fact, below I will argue for some specific ways in which their sense-of-mechanism might need to be adjusted.) However, even if they were not complete experts in this regard, they were still able to complete the task and produce a correct answer. Thus, from the point of view of solving problems, it does not seem to matter very much whether their physical intuition was not fully developed.

This observation leads to the following question: How much work should the sense-of-mechanism and other aspects of physical intuition be able to do? Is it necessary for the sense-of-mechanism to become so finely tuned that it can not only activate both *spontaneous resistance* and *force as mover* , but that it can actually produce the result that these effects precisely cancel? Clearly there are limits to what we need from our physical intuition. Furthermore, these limits are in part

determined by what equations are capable of doing. The equation-using abilities that Alan and Bob have at their command are a powerful tool. Since, Alan and Bob can always rederive this result, it does not need to be wired into their sense-of-mechanism.

This leads to a major conclusion that I want to argue for here: The sense-of-mechanism ñ and intuitive physics knowledge, generally ñ must develop for expertise, but there are limits to how much it must develop. In particular, it does not need to develop so as to be able to make perfect Newtonian predictions. Instead, the requirement is that it develops so as to support and complement work with equations, and other more formal reasoning strategies.

3. When and how do these changes typically occur? What are the crucial experiences that can lead to the "tuning" of intuitive knowledge?

Since physics students spend such a significant amount of time manipulating equations and solving problems, it would be comforting to know that some tuning of the sense-of-mechanism occurs during the equation use that is typical of these activities. Is it possible that any such changes happened during Alan and Bobís work on the Shoved Block problem? To see that this is at least possible, letís start by considering a hypothetical circumstance. Imagine that a student is working to understand a physical situation and two competing and contradictory p-prims are cued to activation. From the point of view of the sense-of-mechanism, this cuing of conflicting p-prims is a problem. Since, in its naive state, the sense-of-mechanism is rather flat and only weakly organized, no p-prim has a much higher priority than any other p-prim. Thus, the p-prim system is not very good at resolving this type of conflict.

Equations and symbol use can provide a way out for this stymied student. It is possible that, by manipulating equations, the student can find a solution to the problem and thus resolve the conflict. If this happens, then it is possible that the priority of the "winning" p-prim will be incrementally increased, and the priority of the losing p-prim will be incrementally decreased. Thus, through such experiences the sense-of-mechanism might be nudged toward alignment with expert intuition. This is a simple story about how work with problem solving might lead to changes in the sense-of-mechanism.

Now letís return to Alan and Bobís work on the Shoved Block problem. First notice that this episode was not exactly the same as the hypothetical circumstance described above, in which the conflict between two p-prims was resolved in favor of one of them. In this case, the result of problem solving did not choose between two competing p-prims; instead, it suggested that both of these intuitions had some validity.

One further observation from my data can help us to make contact with my hypothetical scenario. It turns out that the *force as mover* intuition was somewhat more common and was always produced before the *spontaneous resistance* intuition. Furthermore, only one pair (Mike and Karl) expressed a preference for the second intuition, and even that pair generated the *force as mover* intuition first. Of the other pairs, only Alan and Bob generated the *spontaneous resistance* intuition without some explicit prompting on my part, though all pairs were quick to acknowledge the plausibility of this second intuition.

I therefore speculate that this episode may have the effect of incrementally increasing the priority of the *spontaneous resistance* p-prim. In particular, I hypothesize that this experience may increase the cuing priority of this p-prim for cases in which the mass of an object can be treated as an intrinsic resistance. This is a rather satisfying outcome since the resistance of masses to changes in motion is one of the fundamental aspects of Newtonís laws. In the next passage, Bob sums up the results of this problem. As he does, note that he particularly emphasizes the validity of the *spontaneous resistance* intuition:

> *Bob* So, well, when there isn't like equations down there sort of, I have a tendency just to sort of say: oh yeah, it just=
>
> *Alan* =Right.=
>
> *Bob* =it would slow down quicker. But, so if - I mean, you do - That's what physics is, is you look at the equations and figure it out. But, um, okay=
>
> *Bruce* =So, what do you think of that result that they slow - that they take the same amount of time to stop?
>
> *Bob* Um=
>
> *Bruce* =Is it surprising? Is it not so surprising in retrospect?
>
> *Bob* In retrospect it isn't too surprising. But, um, I mean, I guess, I thought (2.0) Why did I think that the heavier block would slow down quicker? I (Ó) just wasn't, I mean. You're pushing on it - pushing against with a greater force so (Ó) it seems like it would slow down quicker. And that was my first thought. Um, but since it is bigger you obviously need a greater force to stop it. So, I wasn't - I just wasn't thinking about that. I was just thinking: Oh well, you got two blocks. One's experiencing a greater force and one, one - so this one's gonna slow down quicker. But, I mean they're not equal. This one's bigger than this one. Um, so, it isn't too surprising. I mean, it makes sense that, that you need to push, I mean, you got this big boulder coming at you, you have to push harder than if a pebble's rolling at you. Um,, To stop it.

In the above passage, Bob starts off by telling us what his "first thought" was, that the heavier object should slow down faster. But then he goes on to tell us that there is a second effect that must be considered and that, in retrospect, "isnít too surprising." He explains this second intuition with an example: "it makes sense that, that you need to push, I mean, you got this big boulder coming at you, you have to push harder than if a pebble's rolling at you."

The point here is that Bob ends his summary by essentially emphasizing the importance of the intrinsic resistance of masses. Although the *spontaneous resistance* p-prim did not "win" in this problemóthe outcome was a drawófrom Bobís point of view the moral is that the effects of *spontaneous resistance* must not be overlooked. Given his experience in this episode, it is plausible that, in future episodes, Bob will be slightly more likely to see masses as having intrinsic resistance. The priority of the

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spontaneous resistance p-prim has been incrementally increased.

Of course, it would be possible to give other analyses of this episode. The above p-prim account is speculative, and I have not tried to argue against competitors. This is appropriate since my purpose here is only to illustrate, with an example, a possible mechanism through which physical intuition could be altered through quantitative problem solving.

Example 2: A more central role for p-prims

In the above section, I presented a first example in which intuitive knowledge was seen to be involved in physics problem solving, though in a somewhat ancillary role. Now, I want to present an episode in which we begin to see evidence of p-prims playing a more direct role. In this episode, Jack and Jim were asked to solve the following problem, in which a mass hangs at the end of a spring:

> A mass hangs from a spring attached to the ceiling. How does the equilibrium position of the mass depend upon the spring constant, k, and the mass, m?

This problem was relatively easy for these subjects and they spent only about 2 1/2 minutes working on it. Their board work is reproduced in Figure 4.

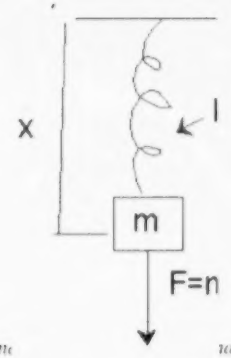

Figure 4 . Jack and *ass on a spring problem.*

Jack and Jim began by explaining that there is a force kx=mg ; downward, a force from the spring acting upward, and that these forces must be equal for the mass to h

Jim Mmm. Well, there's the gravitational fo $x = \frac{mg}{k}$ w down, writes F=ma] And then there is

Jack a force due to the spring // holding it u

Jim // a force due to the spring which I believe is,, [writes F=-kx] is equal to that.

Jack and Jim know that the force of gravity on an object is equal to mg where m is the mass of the object and g is the gravitational acceleration, a constant value. They also know that the force due to a spring is given by the expression $F=-kx$. If a spring is stretched an amount x from its rest lengthóthe length it likes to beóthen it applies a force kx, where k is a constant known as the "spring constant." The negative sign is there because the force is in the opposite direction from the displacement. This expression is one that the students in my study usually knew from memory.

As their next step, Jack and Jim proceeded to equate these two forces, writing $kx=mg$.

> *Jack* So, okay, so then these two have to be in equilibrium since those are the only forces acting on it. So then somehow I guess, um, (3.0) That negative sign is somewhat arbitrary depending on how you assign it. Of course, in this case, acceleration is gravity. Which would be negative so we really don't have to worry about that. So I guess we end up with K X is M G.

In this passage, Jack is trying to deal with a little problem that he has encountered. He knows that he wants to end up with $kx=mg$. But, if he equates the upward and downward forces, then what happens to the negative sign in the expression $F=-kx$ that he has just written? In answer to this problem, Jack makes a pretense of being careful; he says that the acceleration due to gravity is also negative so the negative signs cancel. However, this is not quite up to the standards of a rigorous argument; such an argument would require that Jack carefully associate the signs of terms and directions on the diagram. In addition, a truly careful argument would start by equating the total force with the product of the mass and acceleration: $F_{tot} = ma$, where the total force is the sum of the forces from the spring and gravity, and would proceed by noting that the acceleration is zero:

$$F_{tot} = ma$$
$$F_{spring} + F_{gravity} = 0$$
$$F_{spring} = -F_{gravity}$$
$$mg = kx$$

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The important point here is that Jack does not need to $F_{spr} + F_{grav} = 0$ gorous approach because he knows much of how things should turn out before he even starts. He is not inciples or thinking in terms of the *sum* of two forces, the force from the spring and the force due to gravity. $F_{net} = 0$ Instead, he sees two influences that he knows must be equal and opposite in order for the mass not to move. Since he knows there must be two equal and opposite values, he can just "wave is hands" in order to explain how to make the signs turn out correctly.

This sort of handwaving was common in my data corpus and, I believe, it is indicative of the role that intuitive knowledge plays during problem solving. Other subjectsí solutions to the spring problem looked similar. In some cases, I asked subjects how they knew that the forces of the spring and gravity were equal. Rather than appealing to any physical principles, they seemed to believe that it was simply obvious. After a long discussion, the best that Mike could do was:

Mike How do I know F S equals F G? Because it's in equilibrium.

It is difficult for students to explain the equality of these forces, I believe, precisely because it is directly tied to primitive intuitive notions. I saw similar behavior on other problems. The Buoyant Cube problem, for example, also involves two equal and opposite forces, a force down from gravity and a buoyant force acting upwards (refer to Table 1). Subjects typically began by simply equating these two forces, asserting that they must balance:

Jack Um, so we know the mass going - the force down is M G and that has to be balanced by the force of the wa=

Jim =the displaced water.

These examples are relatively simple, but I believe they help to make the point. Jack and Jim do not need to resort to careful, formal arguments to make everything turn out right in their work with equations. Instead, an intuitive schematization of the situation, as two influences in *balance* , helps to directly guide their work.

As in the previous section, I can make some speculative comments about how the sense-of-mechanism of my subjects is different than that of truly naive subjects. First, I want to note the simple fact that, in this example, p-prims have taken on some dramatically new functions. Initially, the sense-of-mechanism, develops for use in the everyday world, for negotiating and explaining physical phenomena on a daily basis. But, in these examples, p-prims are playing a role in a very different sort of behavior: They are directly participating in problem solving, and are closely linked with equations. I will say more about this in the next section.

In addition, I want to speculate about some possible changes in the organization of the sense-of-mechanism of these subjects. Note that, in all the cases just described, the students were seeing the situation in terms of an active balancing of two agents. This might not have been the case with truly naive subjects. For example, in the case of the buoyant cube problem, it is possible that a naive subject might have said that the water simply "supports" the cube (thus applying the *support* p-prim) rather than seeing this situation as involving the balancing of two opposing forces. The point is not that naive subjects never understand a situation in terms of balanced forces; in some cases they certainly do, as when a hand holds up a pile of books. Rather, the point is that, with the development of expertise, students gradually move toward seeing more and more situations in terms of agency, rather than in terms of constraints. In the episodes just described, we see possible evidence of just such progress.

Example 3: New knowledge, symbolic forms

In introducing the sense-of-mechanism above, I mentioned that diSessa hypothesizes that p-prims might serve as heuristic cues to more formal physics. But, the above example seems to suggest a role for p-prims in problem solving that goes beyond playing a bridging role to the invocation of more formal principles; rather, it appears that it is possible to bypass formal principles altogether and go straight from intuitions to equations. For example, it appears that if a student sees that two influences A and B are in balance, then they know to simply write the equation $A=B$; the intuition directly dictates the form of the expression.

Elsewhere I have argued that this is precisely the case, that there are intuitive schematizations of physical situations that can be directly embodied in equations. (Refer to Sherin, 1996; Sherin, 1997). In some cases, these intuitive schematizations align with specific p-prims. This was the case with the *balancing* examples described just above. However, in general, the story is somewhat more complicated. In the above-cited references, I have argued that a new variety of knowledge develops, which I call "symbolic forms," that mediate the connection between p-prims and equations. I will only be able to briefly summarize this work here.

In brief, each symbolic form involves an association between two components:

Conceptual schema . First, each symbolic form includes a conceptual schema. This schema specifies a few entities and the relationships that hold among those entities.

Symbol template . Second, each symbolic form associates a symbol template with the conceptual schema. The symbol template specifies a framework for embodying the conceptual schema in a specific arrangement of symbols.

Stated very simply, the conceptual schema is the "idea" to be expressed and the symbol template specifies how to represent

that idea in an equation. For example, as suggested above, one symbolic form is what I call *"balancing."* In the conceptual schema associated with *balancing* , a situation is schematized as involving two influences, such as two forces, in balance. Furthermore, the symbol pattern associated with *balancing* involves two expressions separated by an equal sign:

Balancing □ = □

The range of symbolic forms, as found in Sherin (1996), is listed in Figure 5. As with p-prims, I have grouped forms into clusters. For example, in forms in the Competing Terms cluster, the terms in a symbolic expression correspond to influences in competition. Often (but not always) these influences are forces, in the formal sense.

Competing Terms Cluster		**Terms are Amounts Cluster**	
competing terms	□ ± □ ± □Ö	*parts-of-a-whole*	[□ + □ + □ Ö]
opposition	□ ñ □	*base ± change*	[□ ± Δ]
balancing	□ = □	*whole - part*	[□ - □]
canceling	0 = □ ñ □	*same amount*	□ = □
Dependence Cluster		**Coefficient Cluster**	
dependence	[Öx Ö]	*coefficient*	[x □]
no dependence	[Ö]	*scaling*	[n □]
sole dependence	[Öx Ö]	**Other**	
Multiplication Cluster		*identity*	x = Ö
intensiveïextensive	x ↔ y	*dying away*	$\left[e^{-x}\right]$
extensiveïextensive	x ↔ y		
Proportionality Cluster			
prop+	$\left[\frac{\ldots x \ldots}{\ldots}\right]$	*ratio*	$\left[\frac{x}{y}\right]$
prop-	$\left[\frac{\ldots}{\ldots x \ldots}\right]$	*canceling(b)*	$\left[\frac{\ldots x \ldots}{\ldots x \ldots}\right]$

Figure 5 . Symbolic forms by cluster.

As I stated above, in some cases, the conceptual schema matches closely with a particular p-prim. This is the case for *balancing* and *dying away* . However, the majority of symbolic forms donít connect as closely to specific p-prims. In general, they often seem to have wider applicability than p-prims. Here I will just discuss one example involving the *proportionality* (*prop+*) form.

In one of the tasks given to the subjects, they were asked to consider a situation in which an object is dropped under the influence of air resistance. After it is dropped the object gradually speeds up until it reaches a constant speed, the terminal velocity. It is not necessary for me to describe, in detail, how students solved this problem. All that the reader needs to know is that there are two forces involved here, a force from gravity and a force due to the air resistance. Furthermore, it turns out that while all of my subjects knew an expressionóa force lawóthat specifies the force of gravity, $F_g = mg$, most did not know an expression for the force due to air resistance. Although some may have seen such an expression once or twice, it is rare for students to have committed an equation to memory. For this reason, the students had no option but to construct their own

expression for the force of air resistance.

The "right" answeróthe answer you will find in an introductory textbookóis

$$F_{air} = kv^2$$

where v is the current velocity of the object and k is a constant. In general, the students in my study just stated that the force of air resistance should be proportional to velocity, and wrote either the above expression or $F_{air} = kv$. Here are some typical examples:

$$F_{air} = kv$$

Bob Okay, and it gets f-, it gets greater as the velocity increases because it's hitting more atoms (0.5) of air.

$$R = \mu v$$

Mark So this has to depend on velocity. That's all I'm saying. Your resistance - the resistor force depends on the velocity of the object. The higher the velocity the bigger the resistance.

The point here is that, in these instances, students have constructed an expression from an "idea" of what they wanted to express. In this case, they worked from the notion that one quantity should increase as another increases. This is the conceptual schema associated with the *prop+* form. The symbol template associated with this form specifies simply that the relevant symbol is written in the numerator of an expression.

$$prop+ \quad \left[\frac{\ldots x \ldots}{\ldots}\right]$$

Thus, *prop+* is one of the "intuitive" ideas that can be embodied in equations. Similarly, the *prop-* form ("proportionality minus") specifies that a symbol should be written in the denominator, if we want a quantity to decrease as another quantity increases.

What is the relationship between Proportionality forms and p-prims? I hypothesize that these forms are tied to Force and Agency p-prims. In particular, I hypothesize that *prop+* and *prop-* are strongly connected to physical notions of effort and resistance. To illustrate, consider the equation $F=ma$ rewritten as $a=F/m$. The right side of this equation can be seen in terms of the *prop-* formóthe acceleration is inversely proportional to the mass. The hypothesis is that the use of *prop-* here will tend to activate the *spontaneous resistance* p-prim with the mass seen as an intrinsic resistance that resists acceleration. In addition, the right hand side may be seen in terms of *prop+* . Taken together, the activation of *prop+* and *prop-* may tend to cue *Ohmís p-prim* with, in this case, force taken as the effort, mass as the resistance, and acceleration as the result.

Note that, although they may remain connected to p-prims, the Proportionality forms seem to involve more generic relations and less physical meaning than p-prims; proportionality is a more generic relation than that which holds, for example, between an effort and result. This is true because *prop+* applies to any "more implies more" situation, not only to cases where "more effort implies more result."

This lack of "physical meaning" is also characteristic of other symbolic forms, such as the *dependence* form. I believe that this washing out of physical meaning is a fundamental feature of the move from intuitive physics to more expert knowledge. One of the hallmarks of expert physics practice is its ability to quantify the entirety of the physical world; everything is described in terms of numbers and relations between numbers, and all equations look the same whether the quantities that appear are forces or velocities. I call this tension between the homogenizing influence of algebra and the nuance inherent in intuitive physics the "fundamental tension" of physics learning. The set of forms, as I have listed them, constitute the end product of this tension; much of the nuance inherent in intuitive physics is lost, but more distinctions are preserved than those inherent in the syntax of symbolic expressions.

Conclusions

The purpose of this paper has been to begin to go beyond the traditional study of intuitive physics knowledge to an examination of how that intuitive knowledge develops for expertise. In truth, my focus was somewhat narrowed from this broad plan. I restricted my focus to a portion of intuitive physics knowledge that diSessa calls the "sense-of-mechanism," and I adopted diSessaís complex systems account of the nature of this knowledge. Then, I undertook to look for the sense-of-mechanism in the problem-solving behavior of more expert subjects.

Given my approach, there are many caveats to any conclusions that can be drawn. The arguments presented here were based around the presentation of just a few examples. Furthermore, much of my discussion was, by necessity, highly speculative. This was necessary because I am attempting to describe broad processes of change by only looking at one "in between" stage

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in the learning of physics. While I can see p-prims in action in my sample episodes, it is very hard to extrapolate from these episodes to conclusions concerning how the sense-of-mechanism of these subjects is different than that of novices. And, even more difficult, is knowing whether any particular episode has led to enduring changes in the knowledge of particular subjects.

With these caveats in mind, I summarize the answers to my main three questions as follows:

1. **What role, if any, does intuitive knowledge play in physics problem solving?**

   Although the above caveats somewhat limit many of the conclusions that I can draw, I believe that the episodes provide some relatively clear examples in which intuitive knowledge played a role in physics problem solving. Alan and Bob clearly referred to intuitive judgements in their solution of the Shoved Block problem. And, in later examples, I believe it was fairly clear that, at the least, subjects are not strictly following formal rules; they were appealing to common sense. These observations suggested several possible roles for intuitive knowledge in problem solving. Intuitive knowledge can provide a context for interpretation ñ we saw that Alan and Bob understood the outcome of their problem solving work in terms of how it related to their intuitive judgements. Furthermore, in later examples, we saw that intuitive schematizations can drive work with equations in a fairly direct manner.

2. **How does intuitive physics knowledge change in order to play that role, if at all?**

Here I move into more speculative territory. One type of change that I described was changes in the weightings and priorities in the sense-of-mechanism. I commented, for example, on the "refined" intuition that Alan and Bob displayed in their work on the Shoved Block problem. As much as I could tell, the changes in studentís intuitive knowledge was in agreement with the developments predicted by diSessa. There was a movement toward agency-based explanations and away from agency-free p-prims such as *dying away* and *support* .

Along the way, I argued that there are limits to how much it is really necessary for physical intuition to be refined. According to diSessa, the sense-of-mechanism of novices is relatively flat; it has only very local organization with individual p-prims having connections to only a few others. For this reason, it is hard to resolve conflicts between competing intuitive judgements when these arise. However, I believe that it is not necessary to fully remediate this situation since an expert has powerful tools available ñ the ability to use equations ñ that can complement their intuitive knowledge. Thus, I believe that intuitive knowledge must only be refined so as to support and complement work with equations.

I also commented on other types of changes. P-prims take on new functions with the development of expertise; in particular, they come to be used in problem solving. In addition, I argued that a new type of knowledge develops ñ symbolic forms ñ that mediates the connection between p-prims and equations.

1. **When and how do these changes typically occur? What are the crucial experiences that can lead to the "tuning" of intuitive knowledge? In particular, can experiences with quantitative problem solving lead to changes in commonsense physics knowledge?**

In this paper, I argued that intuitive knowledge can change during problem solving. Although this is the most speculative of my contentions, I believe that the evidence presented here makes this contention more plausible. I presented an episode in which a conflict between competing intuitive judgements was resolved during problem solving. It is plausible that such experiences can lead to incremental change in future intuitive judgements. More importantly, I observed that intuitive knowledge can be very directly intertwined in problem solving activities. This observation makes it much more plausible that these activities can lead to changes in that intuitive knowledge: Since it is active, it may very well be changed by these experiences.

In conclusion, these results are very important for the reform of physics instruction and for science instruction broadly. There is wide agreement in the research community that we must have instruction that takes student conceptions into account. But, to do this, we need to know whether intuitive knowledge is truly important for expertise and, if so, the roles it must play. The work reported on here suggests that some intuitive knowledge, modified appropriately, is an essential core component of physics expertise. This implies that, as part of physics instruction, we must take care to address the commonsense knowledge of our students.

However, there is a flip side to these observations. We do want to address studentsí intuitive physics knowledge, but it is not necessary to apply only "conceptual" approaches to instruction in order to address that knowledge. We have seen that physics problem solving does not need to be a purely "formal," "abstract," equation-based activity. Rather, intuitive knowledge and common sense can be very much a part of solving even the most traditional textbook problems. This implies that problem solving need not be irrelevant to the development of expert intuition; in part, intuitive knowledge can be refined within the context of problem solving.

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Appendix A. Key to Transcripts

(Ö)	Text in parentheses indicates transcription uncertain.
(stÖ)	Untranscribed stuttering. Speaker repeats portions of the preceding word or phrase.
//	Start of overlap with another speakeris utterance.
:::	Previous sound is drawn out.
,,	Speaker trails off without finishing statement.
-	Word is cut off.
=	Indicates that there is not the usual amount of silence between two utterances.
(0.0)	A pause, with approximate time in seconds.
hh	Audible breath.
[Ö]	Non-linguistic act.